High-Speed MIMO Communication and Simultaneous Energy Harvesting Using Novel Organic Photovoltaics

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Abstract: A data rate of 363-Mb/s is achieved in a multiple-input-multiple-output experiment using 4 organic photovoltaics as receivers. The same system simultaneously extracted 10.9-mW. The resulting system model predicts 133-Gb/s using a 1000-cell organic solar panel. © 2021 The Author(s)

1. Introduction

The dual use of solar cells as energy harvesting devices and data detectors for optical wireless communications (OWC) has been very promising since it will eventually lead to the realization of self-powered connected devices [1]. The importance of this technology becomes evident knowing that there will be 500 billion Internet-of-Things (IoT) devices by 2030 generating petabyte-scale data in real time [2]. Moreover, light-based wireless communication is a proven solution which can offload a significant portion of the data traffic from the already congested radio frequency (RF) spectrum. To this end, Light-Fidelity (LiFi), defined as a bidirectional, high-speed and fully networked OWC system, is being standardized within the IEEE 802.11bb task group. The basis of digital data encoding in LiFi is the light intensity modulation and direct detection (IM/DD). Photovoltaics (PVs), beside their primary energy harvesting functionality, can detect the rapid change of the incident light intensity. Therefore, incorporating PVs in IoT devices will improve both energy efficiency and data rate in future machine-type communication system. Inorganic semiconductors has been primarily chosen for OWC application, as opposed to organic semiconductors, due to their higher available modulation bandwidth. However, organic semiconductor technology offers a low production cost, thin and lightweight profile, substrate flexibility, and simple integration into a wide range of platforms. Moreover, it has been shown recently that organic light emitting diodes (OLEDs) can provide an electrical bandwidth of more than 240 MHz, enabling gigabit per second (Gb/s) transmission speeds [3], and in this work, we report high speed data detection using novel organic PVs (OPVs) [4]. An important advantage of OPVs compared to their inorganic counterparts is their better suitability for indoor use, which makes them ideal for IoT applications. This is due to the excellent spectral overlap of OPVs, with conjugated organic semiconductors as the light absorbing photoactive layer, with the indoor light spectrum. In this paper, novel OPVs with inverted device architectures are explored along with carefully selected organic photoactive blend systems to combine performance stability and high data rate detection capability. We demonstrate a data rate of 147 Mb/s in a single-input-single-output (SISO) OPV-based system, which is three times the highest reported data rate with an OPV [5]. Also, 3.7 mW is simultaneously harvested by the same system. This is further increased to 363 Mb/s and 10.9 mW by implementing a 4-by-4 multiple-input multiple-output (MIMO) system. The experimental results are used to derive and validate a theoretical model of OPV-based MIMO systems. It is predicted that a solar panel with 1000 single OPV cells and an area of about 0.05 m^2 can achieve over 100 Gb/s of data rate.

2. OPV architecture and performance

As shown in Fig. 1, an inverted configuration of ITO/ZnO/active layer/MoO3/Ag is selected for this work. The inverted device architecture with metal oxide based charge selective transport layers and higher work function metal electrodes such as gold/silver (Au/Ag), have better performance stability compared to the standard structure [6]. The organic photoactive layer is composed of a bulk heterojunction (BHJ) of highly efficient polymer donor, PTB7-Th, with a non-fullerene acceptor, EH-IDTBR, which shows high absorption and efficiency under the visible light spectrum compared to fullerene acceptors [7]. This structure has a great advantage under low intensity indoor illumination because of its high open circuit voltage (~ 1 V) accompanied with a narrow absorption band which leads to a high power conversion efficiency (PCE). The performance of the fabricated OPVs are measured under white LED lighting with an illumination intensity of 5.9 mW/cm^2. The J-V characteristics and the external quantum efficiency (EQE) are shown in Fig. 1. The PCE is 14 % with an output power of 0.83 mW/cm^2. The high PCE can be attributed to the high EQE of the PTB7-Th:EH-IDTBR blend for the emission spectra of white LEDs, which reduces the carrier loss from thermalization and non-absorption. Full details of fabrication process, characterization experiments, and comparison with other blends are presented in [4].
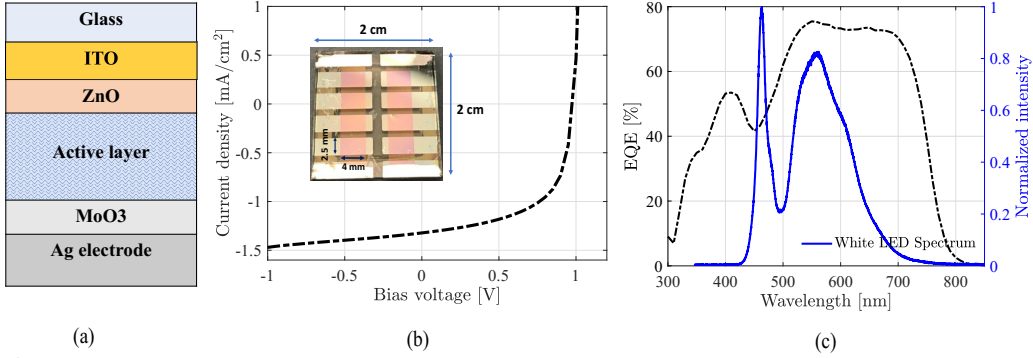
Fig. 1. (a) Schematic of the OPV device architecture (b) J-V characteristics. The inset shows the actual fabricated solar cells with eight individual solar cells (the red areas) on a substrate and four common ground pads at the corners. The eight solar cells have separate contacts so that the output current from each of them is individually accessible. (c) Spectral overlap of the EQE spectra of the PTB7-Th:EH-IDTBR solar cells under white LED illumination with the presented spectrum.

3. Simultaneous data transmission and energy harvesting experiments

The communication performance of the fabricated OPVs is studied by the experimental setup shown in Fig. 2. Red laser diodes (LDs) with a dominant wavelength of 660 nm are used as light sources. Note that white light with a desired temperature can be produced by adding blue and green light sources. Independent direct current biased optical orthogonal frequency division multiplexed (DCO-OFDM) signals are generated and transmitted by LDs that are mounted in lens tubes with an adjustable focal length. A large lens is used at the receiver side to focus each received light beam on one of the OPV cells. The output from each OPV cell is connected to a custom-designed receiver circuit that contains two branches for signal detection and energy harvesting. A capacitor and a load resistor (50 Ω) is incorporated into the signal detection branch of the circuit. A parallel energy harvesting branch contains an inductor and another load resistor (50 Ω) [1]. As shown in Fig. 2, the signal-to-noise ratio (SNR) is measured based on a training sequence, and for comparison, it is also theoretically approximated based on the estimated channel gain, noise power and OPV parameters (capacitance, shunt resistance, etc.). Adaptive bit and energy loading is used with the a target bit error ratio (BER) of 4.7×10^{-3}. The measured -3 dB bandwidth is 2.77 MHz, while 30.1 MHz of bandwidth is adaptively modulated. The power dissipated by the load resistor in the energy harvesting branch is regarded as the harvested power. A data rate of $\rho = 147$ Mb/s and a harvested power of $E_{H=}$ 3.7 mW are obtained in the SISO experiment. For the MIMO experiments, multiple LDs and OPV cells are utilized, and 221 Mb/s or 363 Mb/s of data rate and 6.8 mW or 10.9 mW of harvested energy are achieved by implementing 2-by-2 or 4-by-4 systems. Note that there are some electrical crosstalk between MIMO channels due to the receiver circuit structure, while the optical channel matrix is almost diagonal because of the imaging optics. Zero-forcing (ZF) is used to de-multiplex signals and mitigate the cross talk impact.
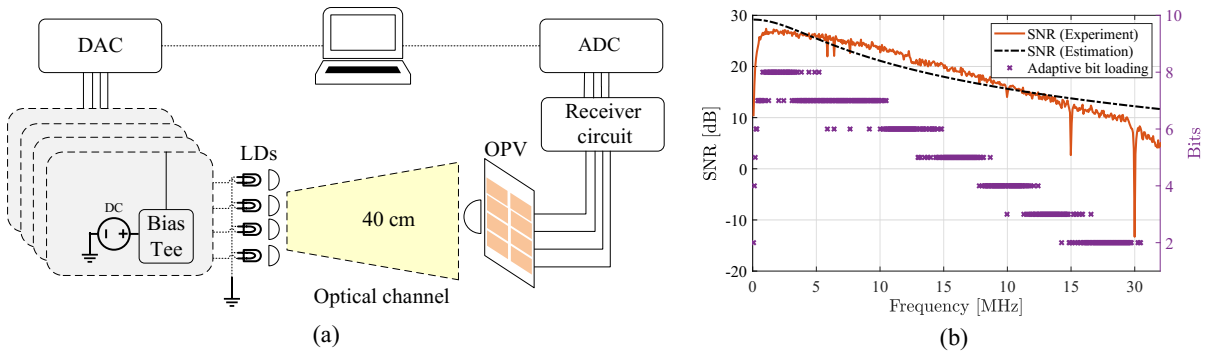

Fig. 2. (a) Block diagram of the system. Analogue-to-digital converter (ADC) and digital-to-analogue converter (DAC) (b) Estimated and measured SNR results and allocated bits according to the adaptive bit loading algorithm.

4. OPV-based MIMO communication achievable data rates

We experimentally demonstrated that high data rates can be achieved with OPVs which also simultaneously act as energy harvesting devices. Measurement results for the channel transfer factors and SNRs are consistent with analytical estimations [4]. Therefore, in this section, the achievable data rates of OPV-based OWC systems are estimated using an analytical model for large numbers of OPV cells. We use the experimental data to extract realistic parameters for the model. The OPVs are connected in series to maximize the harvested energy. The data signal is extracted by an RC circuit from each single OPV cell. The total channel matrix can be estimated for any number of transmitters and receivers by using the estimated channel gain from the SISO experiment and including the effect of the receiver circuit. The electrical channel matrix of the receiver circuit can be derived based on
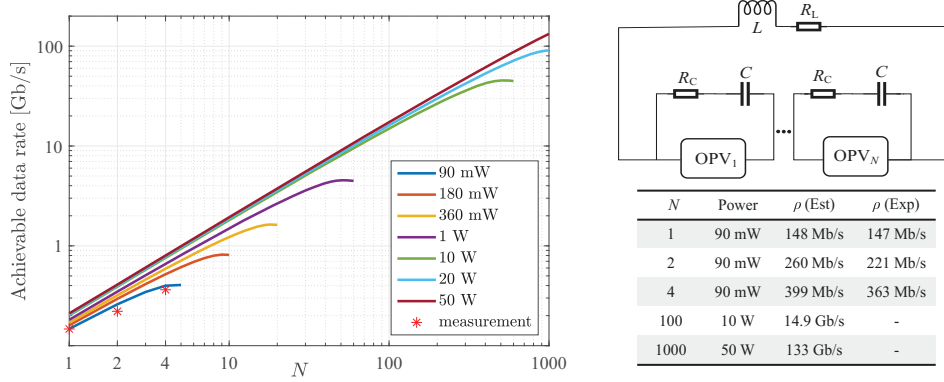
Fig. 3. Acheivable data rates for OPV-based MIMO with N cells. The power values in the figure show the total transmitted electrical signal power. The receiver circuit shown. The table demonstrates the total estimated and experimental data rates, ρ.

the simple series connection of OPV cells as shown in Fig. 3 where OPVs are replaced by their corresponding solar cell electrical circuit model [1]. The parameters of the fabricated OPV cells are measured and validated by standard methods [4]. Equal channel gains are considered for each pair of transmitters and receivers that is a valid assumption based on the obtained 2-by-2 and 4-by-4 experimental results. The communication channel at kth subcarrier can be assumed to be an additive white Gaussian noise (AWGN) channel [8]. For a N-by-N MIMO system, the effective noise consists of thermal and shot noises and is assumed to be white Gaussian $\mathcal{N}(\mathbf{0}, \sigma_n^2 \mathbf{I}_N)$, where $\mathbf{I}_N$ is an ideal matrix. The achievable data rate of the MIMO channel at each subcarrier is expressed as $\rho_k = \Delta f \log_2 |\mathbf{I}_N + (P_{elec}^k / N\sigma_n^2)\mathbf{H}_k^\dagger \mathbf{H}_k|$ where $\mathbf{H}_k$ is the total channel matrix at kth subcarrier, P_{elec}^k is the total input signal electrical power, and Δf is the subcarrier width. Equal total received signal power of 4 mW is observed in all the measurements, and therefore, based on the measured SISO and MIMO channels, the equivalent total transmitted electrical power is about 90 mW. Experimental results and the estimated achievable data rates are shown in Fig. 3 for different numbers of OPV cells. The markers in the figure show the experimental data rates, while lines are estimated for different total transmitted powers. As observed in Fig. 3, there exists a maximum value of the achievable data rate for each value of the total transmit power. Further increasing the number of MIMO channels for a fixed transmit power does not increase the achievable data rate because the transmit power associated with each single channel becomes too small. The table in Fig. 3 compares the experimental data rates and the simulated values. Results confirm that the model estimates values that match the experimental results. It is worth noting that remarkable data rates of 14.9 Gb/s and 133 Gb/s are predicted for $N = 100$ and $N = 1000$, respectively, with total transmitted powers of 10 W and 50 W. The area of the potential solar panel with 1000 cells is only 0.05 m^2 (i.e., 125 OPV panels with 8 individual cells each). This potential system would require a transmitter system with 1000 light sources. The actual system may seem complex when being based on current device technology and communication protocols. However, this will eventually become a reality with the rapid advancements of optical device technologies, such as OLED screen that are now commercially deployed in smartphone displays, as well as massive MIMO communication techniques, which are being tested for commercial use in RF.

5. Conclusion

By designing a novel high-performance OPV structure, efficient energy harvesting and high speed communication was realized under indoor artificial illumination. This system is ideal for indoor applications since the fabricated OPVs show higher PCEs when compared to their non-organic counterparts. Moreover, giga-bit-per-second data rate is predicted for a massive OPV-based MIMO system. Thus, the results of this research are groundbreaking and pave the way for the wide deployment of self-powered IoT devices with high speed wireless connectivity.

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